Positive and negative sequence currents optimization to improve voltages during unbalanced faults

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***Abstract*—Grid faults constitute a series of unfortunate events that compromise power systems. With the increasing integration of renewables and their associated power electronics converters, the injected currents are controllable, but at the same time, they have to be limited so as not to damage the semiconductors. This poses the challenge to determine the combination of currents that improves the most the voltages at the point of common coupling. In this paper, such an issue is approached from an optimization perspective. Solving the optimization problem allows comparing its solutions with respect to the ones obtained by following the grid code control laws. Two fundamental scenarios are presented: one with a single converter, and another with two converters. Several parameters are varied for all kinds of faults to spot the changes on the currents, such as the severity of the fault, the distance of a hypothetical submarine cable, and the resistive/inductive ratio of the impedances. Overall the results indicate that injecting only reactive power is not always the preferable choice. While grid codes are not optimal, they can be regarded as near-optimal decision rules.**

***Index Terms*—Voltage imbalance, Unbalanced fault, Grid code, VSC current saturation, Positive sequence voltage maximization, Negative sequence voltage minimization**

I. INTRODUCTION

THE rise in renewable energies has carried along with it the inclusion of Voltage Source Converters (VSC) as a means of coupling energetic resources to the grid while providing controllability [1]–[3]. Adopting such power electronics equipment has induced a progressive shrinkage on synchronous generators' influence in power systems. Even though synchronous generators suffer an increase in current during faults, which causes protective relays to trigger, the issue is much more prominent in power-electronics-based grids as current spikes are likely to damage the Isolated-Gate Bipolar Transistors (IGBT) found in VSC [4]. Indeed, current (and also voltage) limitations cause VSC to behave differently. They reach what is called a saturated state. Many equilibrium points may arise as a result of that, especially in grids formed by multiple converters operating in critical conditions. The solution to such systems is also likely to become an arduous task to compute, as saturation states are defined by non-linear equations, or in more detail, by piecewise functions.

Not only do currents have to be constrained to not exceed the limitations, but they also have to collaborate on improving the voltages [5]. This becomes visible when looking at the requirements imposed by Transmission System Operators (TSO) in its grid codes [6], [7]. Although this was not the case years ago, when wind power represented a small percentage of the electricity mix, nowadays wind power plants have to control active and reactive power so as to offer frequency support and voltage support respectively [8]. Besides, they have to transiently support the faults. The latter aspect is often referred to as low voltage ride through (LVRT) [9], [10]. The traditional approach to raise the voltage at the point of common coupling is to inject reactive power proportionally to the severity of the fault [8], [11]. During the analysis of faults, it is often the case that voltages are decomposed into positive, negative and zero sequence values. By doing so, the study of the fault is expected to be simplified, and in addition to that, some intuition can be build from inspecting the positive and negative sequence voltages. A concerning unbalanced fault is such that substantially decreases the positive sequence voltage with respect to the nominal voltage while the negative sequence voltage increases. Both sequences have to be thoroughly controlled, as discussed in [11], [12].

Nevertheless, for the most part, grid codes only specify reactive power injection during faults [13], [14]. This makes sense considering that transmission power lines are mainly inductive. When positive sequence reactive currents take negative values, significant voltage drops appear, which aids in increasing the voltage at the point of common coupling. In case negative sequence reactive currents take positive values, the negative sequence voltage diminishes. This strategy is likely to become sub-optimal since transmission lines are not purely inductive. The influence of impedances is covered in [12], where the authors express the currents to inject as a function of the voltage and the impedances. A recursive relation between the voltage and the current is found, which invalidates the possibility of working with a closed-form expression from where to compute the optimal currents solution. Expressions of the same nature are proposed in [15], where instead of attempting to solve the optimization problem, a control parameter is introduced. This takes various values, but no analysis is carried out to determine the optimal choice. The effect of varying this control parameter is studied in [16], although it is not computed with a systematic approach, but rather, manually. Reference [17] proposes a maximum allowed support (MAS) control scheme that is said to provide the maximum voltage support and simultaneously satisfying the current limitations. The study does not explicitly indicate how the current is distributed among the real and the imaginary positive and negative sequence components, and variations in input parameters are rather limited. Another voltage support scheme is presented in [18], where the injected currents depend neither on the active power nor the filter resistance. In addition, positive and negative sequence grid voltage values are imposed, which facilitates the obtention of the steady-state current values. A variation of the grid code requirements is depicted in [19]. The authors found it to provide better results than conventional grid codes. The

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majority of the grid support strategies described above are compared and summarized in [20]. It is worth mentioning that the systems under study considered in these references include a single VSC. Further conclusions are expected to be extracted from examining a two-converter case study.

Consequently, the problem has to be presented as an optimization problem, where the objective is to maximize the positive sequence voltage and/or minimize the negative sequence voltage, all this constrained to not surpass the current limitations. This paper solves precisely the above-mentioned optimization problem. Two other control rules are implemented. One focuses on solving the optimization problem but in addition to the other constraints, it is restricted to only injecting reactive power. The third control rule follows the implementation of grid code specifications with its characteristic droop profile. These three options are tested for both balanced and unbalanced faults, where this last category includes the line to ground, the line to line and the double line to ground faults. First, a basic system with a single converter is studied. Then, the analysis is repeated for a system with two converters in order to identify their interaction in saturated states.

The structure of the paper is as follows. Section II formulates the optimization problem and details the methodology employed. Section III presents the results together with the corresponding discussion for a single converter case. Section IV analyzes similar situations for a basic power system with two converters. Finally, Section V concludes this work.

II. Problem formulation

Given a basic system as the one depicted in Figure 1, the goal is to optimize the voltages at the point of common coupling. The fault is symbolized by a fault impedance, which in reality can either represent a balanced or unbalanced fault.

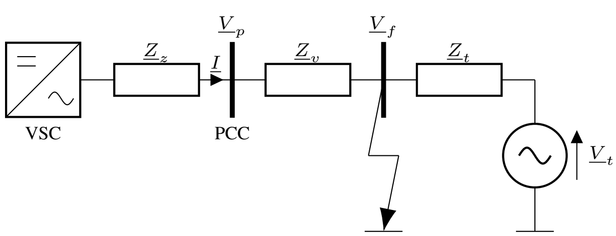

Fig. 1: Single-phase representation of the basic system under a fault

The VSC is typically modeled as three-phase voltage sources in series with the filters impedance of the form $\underline{Z}_z$. Its control strategy directly adjusts the voltages to so that currents can indirectly meet the references [21]. However, the approach followed here consists of treating it as a current source that injects a current $\underline{I}$ into the system. This is precisely the variable to control in order to improve the voltage $\underline{V}_p$. Such current it constrained to not provide any zero sequence component and simultaneously respecting the limits. Therefore, the optimization problem reads as

$$\begin{aligned} \min_{\underline{I}} \quad & \lambda^+|(1-|\underline{V}_p^+(\underline{I})|)| + \lambda^-|(0-|\underline{V}_p^-(\underline{I})|)| \ , \\ \text{s.t.} \quad & \max(\underline{I}^a,\underline{I}^b,\underline{I}^c) \leq I_{\max} \ , \\ & \underline{I}^a+\underline{I}^b+\underline{I}^c = 0 \ , \end{aligned} \tag{1}$$

where the positive and negative sequence components of voltage $\underline{V}_p$ are symbolically expressed as functions of the currents, and $I_{\max}$ is the maximum allowed current by the converter. Considering that faults are strong enough so that the converter is incapable of raising the voltage $|\underline{V}_p^+(\underline{I})|$ to values higher than 1, the optimization problem can be rewritten:

$$\begin{aligned} \min_{\underline{I}} \quad & \lambda^+(1-|\underline{V}_p^+(\underline{I})|) + \lambda^-(0-|\underline{V}_p^-(\underline{I})|) \ , \\ \text{s.t.} \quad & \max(\underline{I}^a,\underline{I}^b,\underline{I}^c) \leq I_{\max} \ , \\ & \underline{I}^a+\underline{I}^b+\underline{I}^c = 0 \ . \end{aligned} \tag{2}$$

Removing the outer absolute values has been proved to be beneficial in terms of computational time. The voltages are related to the currents by means of Kirchoff's laws. To compact the problem, the Thevenin grid equivalent has been transformed to a Norton equivalent with currents $\underline{I}_t = \underline{V}_t/\underline{Z}_t$. Therefore:

$$\begin{pmatrix} \underline{I}^a \\ \underline{I}^b \\ \underline{I}^c \\ \underline{I}_t^a \\ \underline{I}_t^b \\ \underline{I}_t^c \end{pmatrix} = \mathbf{Y} \begin{pmatrix} \underline{V}_p^a \\ \underline{V}_p^b \\ \underline{V}_p^c \\ \underline{V}_f^a \\ \underline{V}_f^b \\ \underline{V}_f^c \end{pmatrix} \ , \tag{3}$$

where for a system as the one depicted in Figure 1 the admittance matrix $\mathbf{Y}$ is a 6×6 matrix which can be flexibly constructed depending on the grid impedances $\underline{Z}_v$, $\underline{Z}_f$ and $\underline{Z}_t$. Finally, the sequence components of the voltages are obtained by means of Fortescue's transformation [22]:

$$\begin{pmatrix} \underline{V}_p^0 \\ \underline{V}_p^+ \\ \underline{V}_p^- \end{pmatrix} = \frac{1}{3} \begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix} \begin{pmatrix} \underline{V}_p^a \\ \underline{V}_p^b \\ \underline{V}_p^c \end{pmatrix} \ , \tag{4}$$

where $a = e^{j\frac{2\pi}{3}}$.

Although the study can also be performed in the sequence components reference frame as in [23], each type of fault has to be studied individually. Consequently, even if both approaches have been proved to be generate the same results, this paper opts for analyzing the faults in the natural reference frame for greater simplicity.

III. Single converter case study

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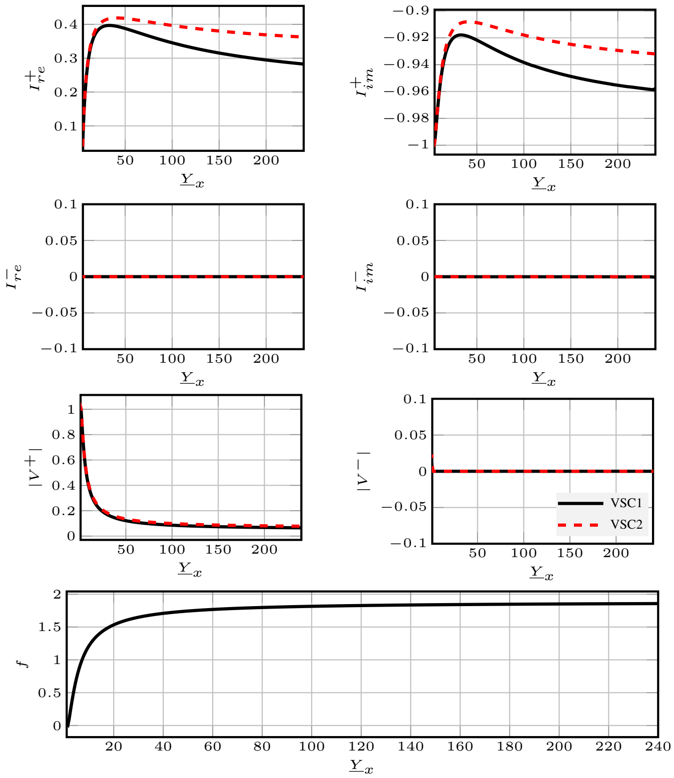

Fig. 2: Influence of the currents on the objective function for the balanced fault with a varying fault admittance

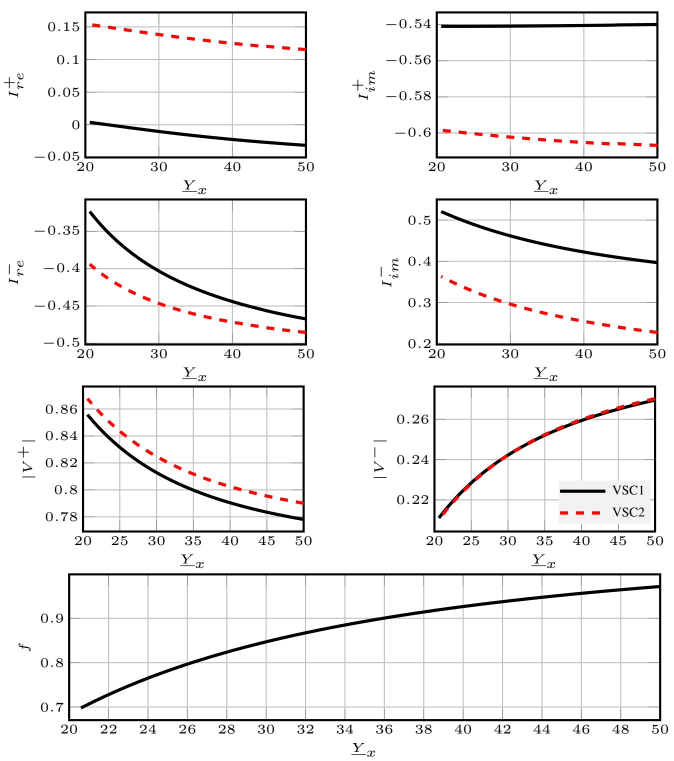

Fig. 3: Influence of the currents on the objective function for the line to ground with a varying fault admittance

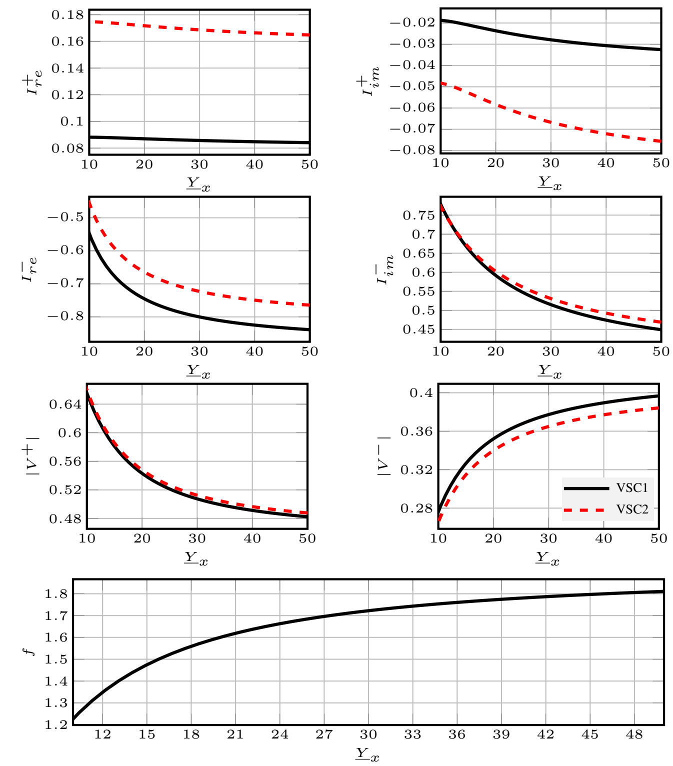

Fig. 4: Influence of the currents on the objective function for the line to line with a varying fault admittance

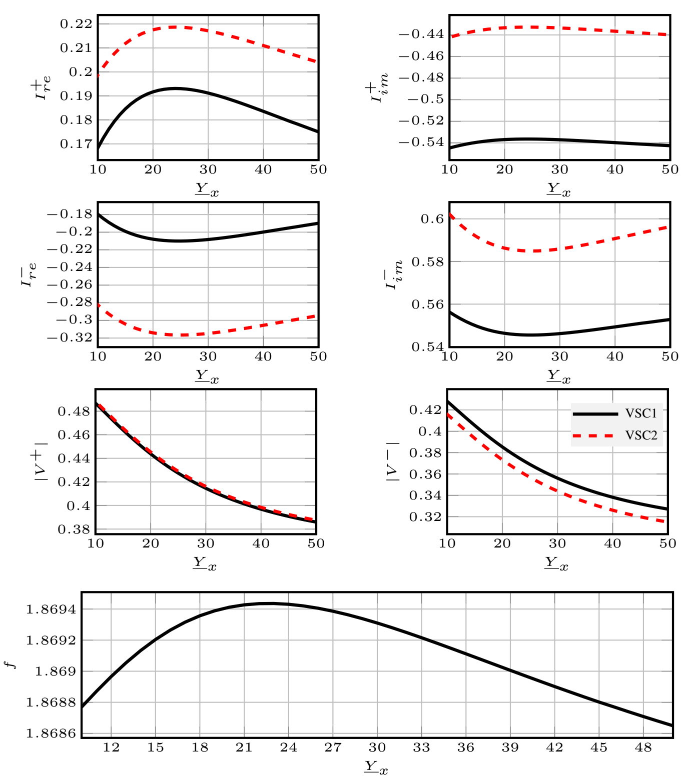

Fig. 5: Influence of the currents on the objective function for the double line to ground with a varying fault admittance

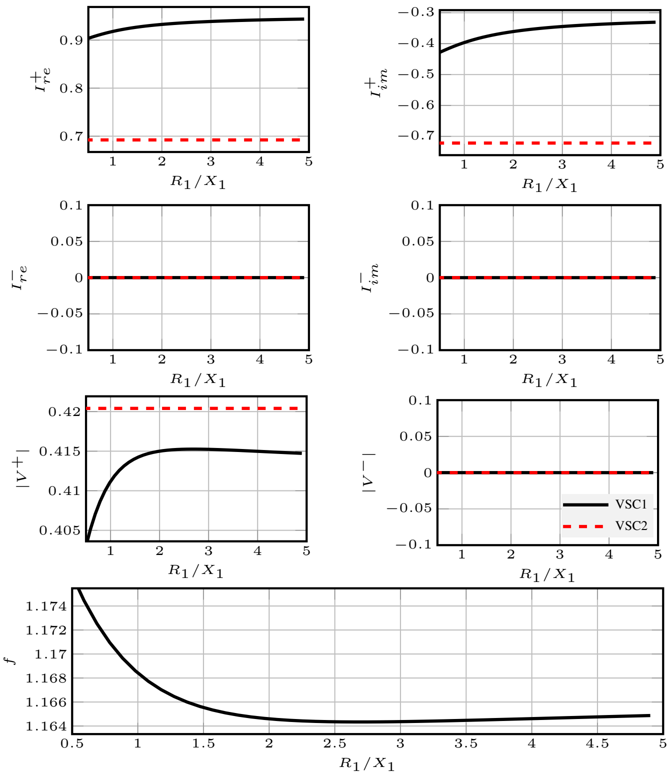

Fig. 6: Influence of the currents on the objective function for the balanced fault with a varying R_1/X_1 ratio and $\underline{Y}_x = 10$

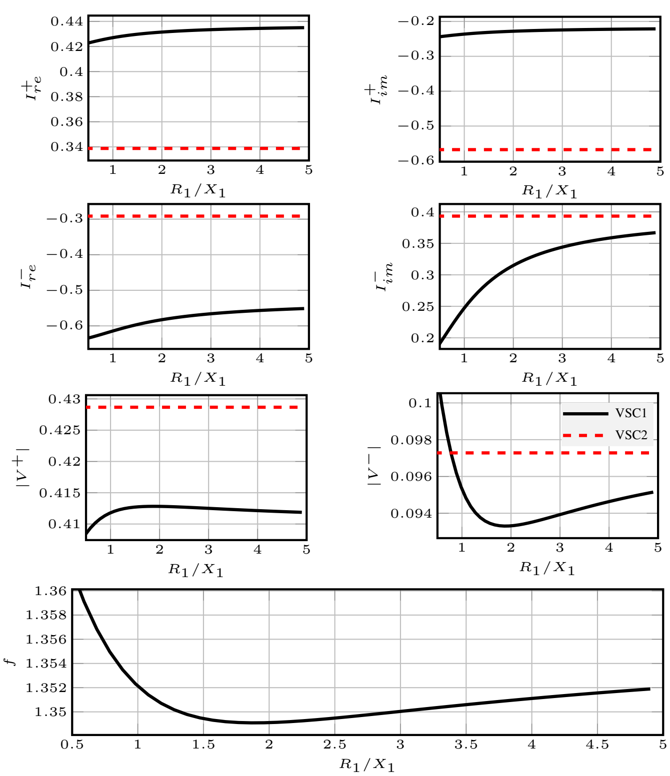

Fig. 7: Influence of the currents on the objective function for the line to ground fault with a varying R_1/X_1 ratio and $\underline{Y}_{ag} = 25$

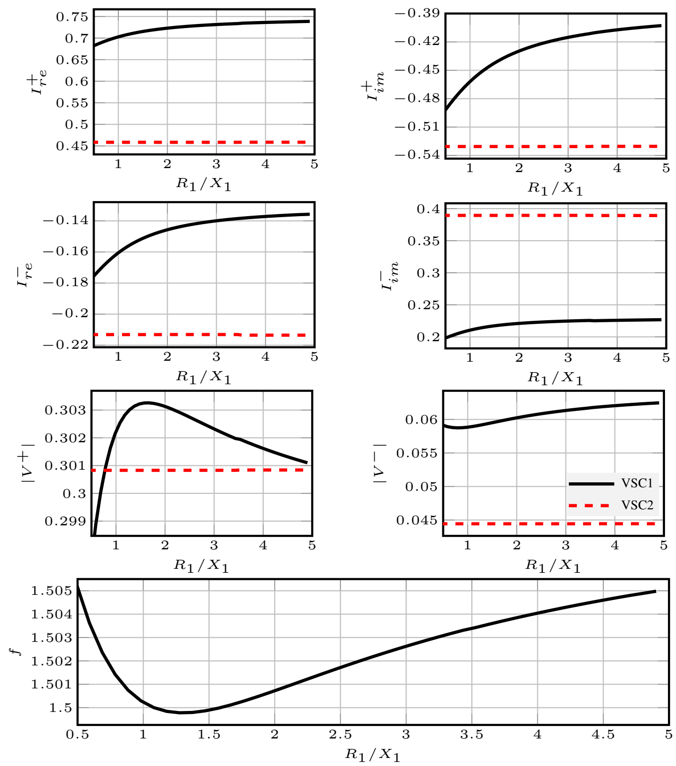

Fig. 8: Influence of the currents on the objective function for the line to line fault with a varying R_1/X_1 ratio and $\underline{Y}_{ab} = 25$

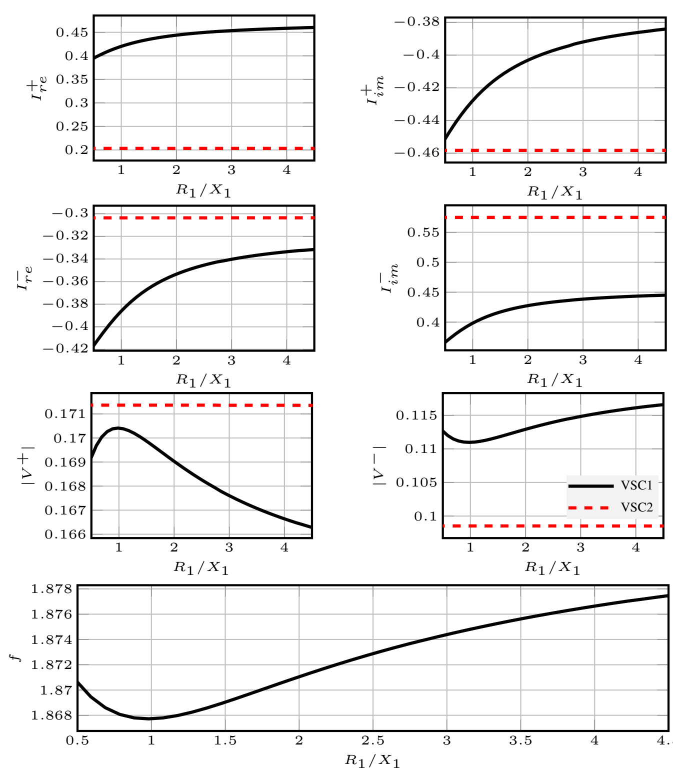

Fig. 9: Influence of the currents on the objective function for the double line to ground fault with a varying R_1/X_1 ratio and $\underline{Y}_{ag} = 25$

IV. Two converter case study

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V. Conclusion

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